Chapter 15

Space Weather Effects on Power Transmission Systems: The Cases of Hydro-Québec and Transpower New Zealand Ltd

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Abstract Space weather has long been known to effect electric power systems, these effects can range in scale from the barely noticeable to the catastrophic. This paper reviews two events , one the 1989 collapse of the Hydro-Québec system which ranks as probably the most significant power system event tracable to geomagnetically induced currents and two, the 2001 event on the Tranpower system in New Zealand, which while significantly less severe did cause plant failures on a system that had no previously considered geomagnetically induced currents a threat to power quality and security of supply

Keywords Electric Power Transmission, Geomagnetic Storms, Geomagnetically Induced Currents, Transformer Saturation, Hydro-Québec, Transpower New Zealand

1. INTRODUCTION

This paper presents two occurrences of geomagnetically induced current (GIC) that have affected high voltage networks situated almost to the antipodes one from the other. During the first event on March 13 1989, the whole 735 kV network of Hydro-Québec in Canada collapsed, causing a blackout which affected several million people. This case is well known and here we put the emphasis on preventive and corrective actions that have been taken since then to avoid a repetition of such an event in the future.

I.A. Daglis (ed.), Effects of Space Weather on Technology Infrastructure, 287-299.

The second case took place in New Zealand, where Transpower is the owner and operator of the High Voltage AC and DC power grid. On November 6 2001 Transpower experienced the first known disruption to its grid system caused by GIC. We present the events of the day and attempts to mitigate the risks. We also discuss the damage caused by this storm and the operational procedures put in place to manage this risk.

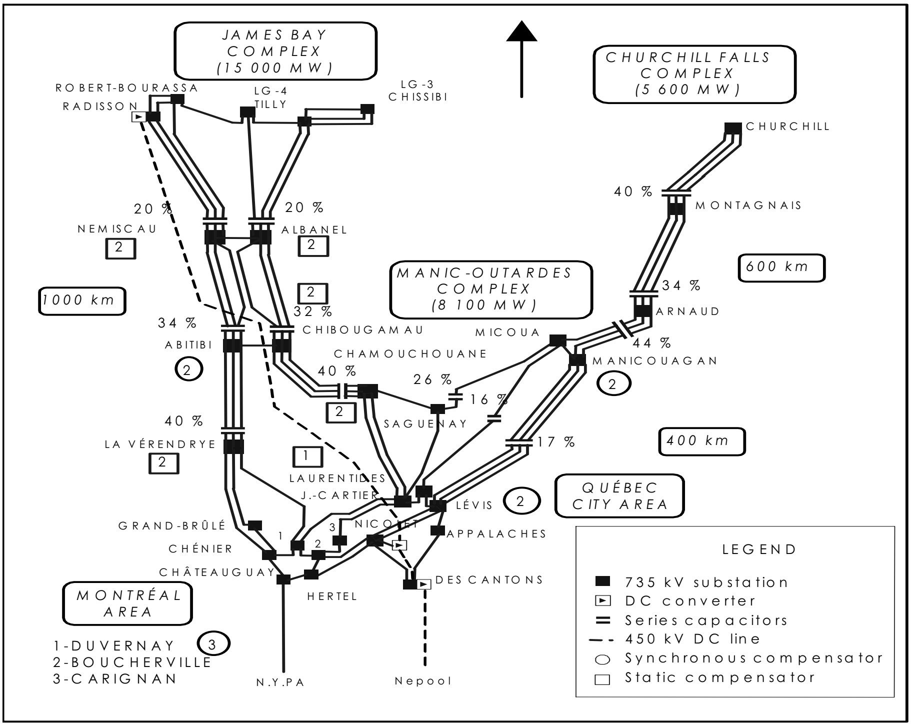

Figure 1. The Hydro-Québec's 735 kV transmission network.

The present Hydro-Québec 735 kV main transmission network is illustrated in Figure 1. The system has 35000 MW of generation with more than 90% from hydro-electric sources. Two major corridors, each 1000 km long separate the major production centers from the main load situated in the Québec and Montréal area. The long lines and poor ground conductivity over most of the northern region make the system susceptible to GIC. System operation is supported by 11 static compensators (7 were in place in 1989), and (since 1995) series compensation on some corridors.

On March 12 1989, voltage instabilities occurred in the evening and had to be corrected by network operators. During the night (March 13) at 02:45 Eastern Standard Time, all 7 static compensators on the James Bay corridor tripped in less than one minute. Voltage started to collapse and the James Bay complex separated 8 seconds later. Power oscillations caused Churchill Falls to separate also after 6 seconds. Finally, the complete network collapsed less than 20 seconds following the separation of Churchill Falls.

More than a decade later, a very different story happened in another part of the world. The High Voltage electric power transmission system in New Zealand is owned and operated by Transpower New Zealand ltd.

The system is composed of a 220kV and 110 kV AC system on each of the two main Islands joined by a HVDC link. Up until the time of this event Geomagnetically Induced Currents (GIC) had not been recorded on the power system and no damage had been reported. The risks to the power system due to GIC events has been considered to be low due to several factors including:

- The power system has relatively short spans, and covers a short distance when compared to Canada or the USA.
- The natural geography aligns the system on a North /South basis.
- The use of Neutral Earthing Resisters on many transformers.
- New Zealand has a mid latitude position

The utilisation of neutral resistors is justified by a particular need. The South Island of New Zealand has an abundance of hydro generation, which is transmitted, to the more populous and industrial North Island by the use of an HVDC link. At times the return path for the electric current is the ground itself, which can cause problems due to the earth currents rising up through the earthed points of power transformers and onto the AC system as this forms a low resistance path back to the HVDC terminal station.

To prevent this occurrence Neutral Earthing Resistors (NERs) were fitted to the earthed point of the Transformers ‘Star’ windings. These resistors were fitted with Supervisory Control and Data Acquisition (SCADA) monitoring and alarms. Power system operators monitoring these currents and alarms are instructed to re-configure the HVDC equipment when alarms are received.

Despite these factors on 06 November the 2001 a Kp 8 GIC event occurred causing the loss of voltage support equipment and the destruction of a power system transformer.

In Section 2, this paper discusses several actions that have been undertaken at Hydro-Québec to avoid a similar event in the future. Section 3 is devoted to the Transpower case.

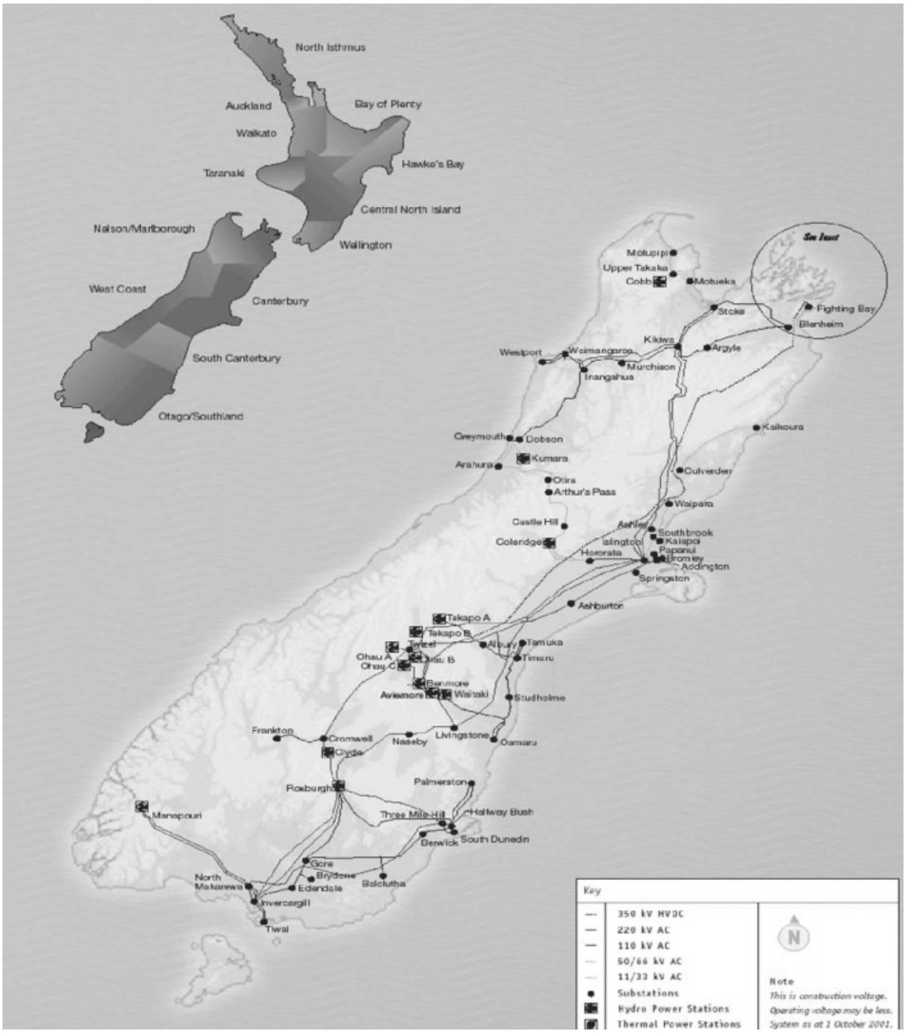

Figure 2. The Transpower New Zealand transmission network.

2. PREVENTIVE AND CORRECTIVE ACTIONS AGAINST GEOMAGNETIC ACTIVITY AT HYDRO-QUEBEC.

Actions have been taken in three different areas: measurement systems and alert services, safe network exploitation rules during geomagnetic activity (measured or predicted) and finally, network modifications.

2.1 Measurement systems and alert service

2.1.1 The voltage phase angle measurement system

The first version of this system has been put in operation about 20 years ago. Over the years several improvements have been implemented. The present version has been running since the end of 1995.

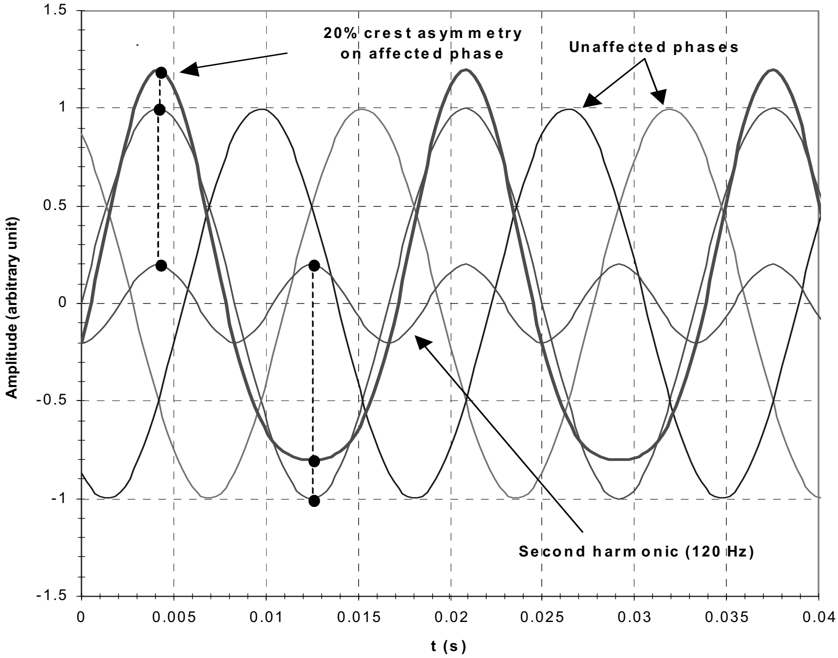

Figure 2. Even harmonics and crest asymmetry.

The system uses 8 measurement units, each of them located in a different 735 kV substation. Each unit measures and transmits the voltage phase angle, the frequency and the positive and negative crest voltage at every cycle, i.e. 60 times/s. Using dedicated phone lines and modems those data are transmitted in real time and on a permanent basis to a central acquisition unit. At this location, some data are recorded for post-mortem studies when specific triggers are exceeded. Other data are processed (to drastically reduce bandwidth and also to eliminate transmission errors) and forwarded in real time to the power system control center.

The crest voltage measurement enables the central acquisition unit to calculate the crest voltage asymmetry at every cycle. Numerical filtering is used to increase signal/noise ratio and resolution of the measurement. As shown in Figure 2, the asymmetry is a way to detect even harmonics which might be produced if geomagnetically induced currents circulate in the neutral of power transformers. Asymmetry level from each measurement unit is received at the control center every 5 seconds; immediate alert is generated as soon as a minimal level is exceeded (currently between 2.2 and 3.0% depending on the substation).

The whole system is currently being improved. New measurement units will use GPS synchronization. Instead of transmitting crest voltages that could be affected by harmonics, those units will measure the direct sequence voltage phasor, a parameter combining amplitude and phase information that is less sensitive to harmonics and more representative of the "true" voltage in most circumstances. Also, the frequency content up to the 8th harmonic will be calculated using a fast Fourier transform algorithm. Single-phase data coming from up to four lines will be transmitted once every four seconds.

2.1.2 The Geomagnetic storm detection system (DOGME)

This second measurement system has been build to act as a backup for the SMDA. As a consequence its measurement capability are limited and strictly oriented toward low bandwidth, geomagnetically induced current effects.

The system has a measurement unit in four 735 kV substations. Each of them measures the second and fourth harmonics level on the line voltage, and transmits this information in real time to the control center. Data is logged on a permanent basis. An alert is generated when the sum of harmonics 2 and 4 is greater than a given threshold (actual value is 3%).

Data from the DOGME system can be visualized using a web page available to the network operators and other people. This page presents plots of harmonics levels at every measurement point. It also includes pointer to the estimated real-time Kp index produced by the NOAA Space Environment Center. Pointers to the SMDA data acquired by the control center are also included.

2.1.3 Geomagnetic alert from specialized provider

Real time measurement of crest voltage asymmetry and harmonic level enables us to know when geomagnetic effects are present but unfortunately without any lead time.

Solar magnetic disturbance (SMD) alert service used by Hydro-Québec is available on a permanent basis. An expert is *always* validating data at all time. Alert are sent only if a well-identified event exceeding a minimal threshold is detected, or if its probability of occurrence is high. All alert messages are short and clear. They are to be read by network operators, not SMD experts. Alerts transmission is done by e-mail, fax and pager. Finally, all alerts are followed by an end-of-alert message, to tell the operators when they can resume normal network operation.

2.2. Special Exploitation rules during geomagnetic activity

To maximize the stability margin during geomagnetic activity (predicted by an alert or measured using the SMDA or DOGME systems), Hydro-Québec uses specific exploitation rules to operate its network in such situation.

- During a storm exceeding a given threshold, the maximum transit capacity of all major lines is reduced by 10%, relative to the normal case.
- Maximize the number of lines in service and the spinning reserve.
- Suspend test in progress.
- Minimize maneuvers to avoid instability.
- The threshold is actually set at 2.2% crest voltage asymmetry on SMDA, or storm of intensity Kp = 8 or greater.

The 10% transit reduction is based on a Northeast Power Coordinating Council (NPCC) policy to limit to <90% of their security limit the maximum transit of all "critical" interconnections. NPCC's document "Procedures for Solar Magnetic Disturbances" (document "C-15") basically states what follows:

- Suspend maintenance and restore HV lines.
- Adjust loading of HV dc circuits from 40% to 90% of their nominal rating, and critical transmission lines at <90% of their security limit.
- Reduce the loading of generator operating at full load to increase spinning reserve.
- Maximize the reactive power reserve by using equipment capable of synchronous condenser operation.
- Ensure with personnel that SMD monitoring equipment is in service.

Additional information about the NPCC (members, area covered...) can be found on the web at www.npcc.org.

2.3 Modifications to the network.

2.3.1 Corrective action on static compensators.

Following the 1989 event, examination of static compensators revealed that their protection limit was set too low. For this reason the tripping limit has been significantly raised on a permanent basis. Moreover, during a geomagnetic alert condition, the tripping is blocked and reduced to an alarm signal only. Note that the total number of static compensators is currently 11 (7 in 1989).

2.3.2 Addition of series compensation.

On a transmission line, series compensation means that capacitors are added in *series* with that line. This has two important effects. The first one (and the most important) is that a series compensated line appears to be electrically shorter than an uncompensated one: it becomes more "rigid". The direct consequence is an increased stability, i.e. a network less susceptible to power oscillations. This better stability can be used to increase the power delivered by parts of the network. The second and very fortunate effect is that since a capacitor blocks any DC current, it also blocks GIC since they are quasi DC currents.

The addition of series compensation on several 735 kV lines (completed in 1996) is mostly justified by its positive effects on the stability of the network and was planned before the 1989 event. After the blackout a review of this decision took place and it has been concluded that by stopping the circulation of DC current over many lines, less harmonics would be produced by GIC. The location of blocking capacitors is indicated on Figure 1.

Actual measurement of the crest voltage asymmetry by the SMDA seems to indicate lower values than before, but it is difficult to conclude firmly. Table 1 gives maximum asymmetry levels observed during major between years 1998 and 2001. Those are to be compared with levels in excess of 10% observed in the past.

	Geomagnetic storm		
Date	**Geomag. Intensity**	**Max. Asym. (SMDA)**	**735 kV substation**
20010411	K 8	1,6	Micoua
20010331	K 9	3,9	Micoua
20000715	K 9	4,3	Châteauguay 765
20000406	K 8	7,6	Châteauguay 765
19991022	K 8	2,2	Micoua
19981107	K 8	2,5	Tilly
19980925	K 9	1,9	Micoua
19980827	K 8	1,6	Micoua
19980806	K 8	1,8	La Grande 2P
19980504	K 9	3,1	Micoua

Table 1. Maximum asymmetry level (1998-2001).

2.3.3 Addition of the automated operation of shunt inductors system (MAIS system).

Another modification to the network is the MAIS system, which is operational since 1995. Its main objective is to help in the dynamic control of the voltage following major events.

In each substation the MAIS control unit may use local voltage, frequency and reactive power as decision variables. In general, reactors are switched using only voltage threshold and voltage rate of change.

The system increases the stability of the network and helps the static and synchronous compensators to maintain adequate voltage.

3. GIC EFFECTS AT TRANSPOWER ON NOVEMBER 6 2001; MITIGATION AND RISK MANAGEMENT

3.1 The event

On 6 November 2001 at 14:53 (New Zealand summer time) Alarms from NERs across the South Island were received by the HVDC operator. Simultaneously the Static Var Compensator (Voltage control equipment) for Christchurch city (latitude 43.53) tripped along with a transformer feeding Dunedin city (latitude 45.85).

A fault on the HVDC was quickly eliminated as a cause, and it took another 15 to 20 minutes for people to start suspecting a GIC event.

Confirmation was found by hunting on the Internet and finding a warning on the NOAA Space Environment Center web-site (www.sec.noaa.gov).

While no further damage was sustained NER alarms remained active for many hours after the initial event.

Figure 3 shows the onset of the GIC and the rise in current through the NER on transformer T13 at a hydro power station 'Ohau C' (OHC). The magnetic data is the horizontal component and is recorded at Eyrewell magnetic observatory in Christchurch (latitude 43.25). There is a strong correlation between the change in nT over time and the level of induced current through the transformer NER.

3.2 Equipment damage.

The transformer at Dunedin / Halfway Bush (HWB T4) was of unit construction i.e each of the 3 phases is a separate physical unit. The transformer tripped on red phase Buchholz sudden oil pressure protection and a dissolved gas analysis indicated a major internal flashover.

The remaining units were unaffected and a spare unit replaced the damaged red phase and the transformer was back in service in a matter of hours.

An internal inspection revealed damage to the insulation material. The transformer was beyond repair and it was subsequently written off. Subsequent to this event almost a year later a close in ground fault caused another phase of this transformer to be damaged in a simular way, once again it was beyond repair.

The GIC took affect on all concerned items of equipment at 14:52. The Transformer T4 at Halfway bush failed within one minute of this occurrence. It does not seem possible for a transformer of this sort to fail this quickly due to saturation of the core creating hotspots etc. However, deterioration of transformers is cumulative and caused by events such as power system faults, electrical overloading GICs etc which over time degrades the transformer. It is possible that the transformer was already prone to failure and the GIC was the final contributor, hence failing very soon after the event.

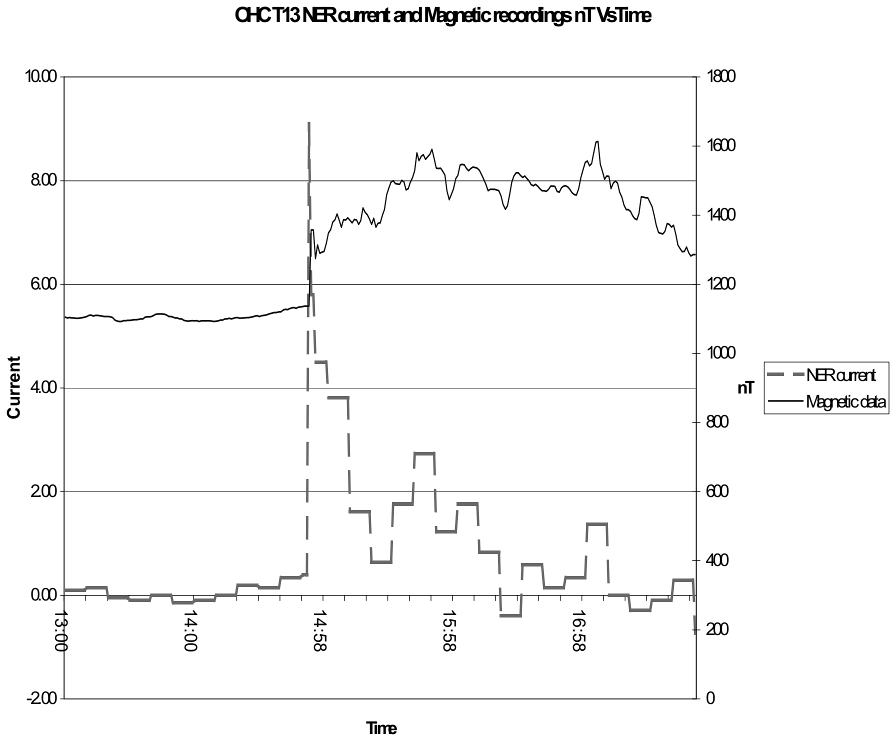

Figure 3. OHC T13 NER current and magnetic recordings (nT) vs time.

The SVC device at Christchurch (Islington) was not damaged at all by the event, the SVC was ‘tripped’ by the negative sequence over-current relay. This protection has operated previously and in all cases 2nd harmonic (transformer saturation) was present in the waveform.

This tripping is considered to be a fault in the protection system and counter measures have been applied.

3.3 Introduction of contingency plans.

Transpower has subsequently implemented plans in an effort to prevent further events on the power system.

We now subscribe to the NOAA SEC warning system and on receipt of a warning a communications and operational process is put in place. The object of the operational process is to reduce the amount of geomagnetically induced current into the system and manage operations and maintenance work so as to minimise the impact. Power flow studies are undertaken to ascertain whether certain transmission circuits with an east/west aspect can be removed from service. Likewise for vulnerable interconnecting transformers. At the onset of NER alarms the equipment is removed.

3.4 The New Zealand electricity market

A competitive electricity market operates in New Zealand. This market uses a nodal pricing model. This system is also use in many other Electricity Markets and means that each ‘node or point of supply has a different price representing the cost of losses and constraints involved in supplying electrical energy to that point.. Removing equipment from service can therefore have an effect on the price of electricity. While the equipment we remove is spare capacity it may still affect prices under many generation profiles. This then gives us another direct cost of GIC events. Processes are also in-place to calculate these in the event of the plan being enacted.

4. CONCLUSION

Following the 1989 event, Hydro-Québec took several remedial actions:

- To receive geomagnetic alerts from specialized organizations.
- To operate real time measurement systems able to detect GIC effects and to alert immediately the network operators.
- To apply conservative exploitation rules during strong geomagnetic activity, measured or predicted.
- To modify the protection of its static compensators.
- The addition of series compensation and the automated operation of shunt inductors system both ensure a more robust network, less susceptible to GIC disturbances.

We now think that our main network can operate correctly during any realistic geomagnetic storm.

At Transpower, the contingency plans were used on several occasions during the GIC events in November 2003 there was an immediate reduction in the NER currents which may suggest that the plans were effective, a more detailed analysis is required however before a final conclusion can be made.

5. ACKNOWLEDGEMENTS

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